



HAL
open science

Inferior T cell immunogenicity of a *Plasmodium berghei* model liver stage antigen expressed throughout pre-erythrocytic maturation

Matthew P Gibbins, Katja Müller, Kai Matuschewski, Olivier Silvie, Julius Clemence R Hafalla

► To cite this version:

Matthew P Gibbins, Katja Müller, Kai Matuschewski, Olivier Silvie, Julius Clemence R Hafalla. Inferior T cell immunogenicity of a *Plasmodium berghei* model liver stage antigen expressed throughout pre-erythrocytic maturation. *Parasite Immunology*, 2021, 10.1111/pim.12877 . hal-03371270

HAL Id: hal-03371270

<https://hal.sorbonne-universite.fr/hal-03371270v1>

Submitted on 8 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

BRIEF REPORT

Inferior T cell immunogenicity of a *Plasmodium berghei* model liver stage antigen expressed throughout pre-erythrocytic maturation

Matthew P. Gibbins¹  | Katja Müller^{2,3}  | Kai Matuschewski^{2,3}  | Olivier Silvie⁴  | Julius Clemence R. Hafalla¹ 

¹Department of Infection Biology, Faculty of Infectious and Tropical Diseases, London School of Hygiene and Tropical Medicine, London, UK

²Parasitology Unit, Max Planck Institute for Infection Biology, Berlin, Germany

³Institute of Biology, Humboldt University, Berlin, Germany

⁴Sorbonne Université, INSERM, CNRS, Centre d'Immunologie et des Maladies Infectieuses, CIMI-Paris, Paris, France

Correspondence

Julius Clemence R. Hafalla, Department of Infection Biology, Faculty of Infectious and Tropical Diseases, London School of Hygiene and Tropical Medicine, London, UK.
Email: Julius.Hafalla@lshtm.ac.uk

Present address

Matthew P. Gibbins, Wellcome Centre for Integrative Parasitology, Institute of Infection, Immunity and Inflammation, University of Glasgow, Glasgow, UK

Funding information

European Commission, Grant/Award Number: #34; Chica and Heinz Schaller Foundation, Grant/Award Number: ANR-11-LABX-0024; The Royal Society, Grant/Award Number: UF0762736, UF120026 and RG130034; National Centre for the Replacement, Refinement & Reduction of Animals in Research, Grant/Award Number: NC/L000601/1

Editor: Eleanor Riley

Abstract

Sporozoite antigens are the basis of a number of malaria vaccines being tested, but the contribution of antigens expressed during subsequent liver stage development to pre-erythrocytic stage immunity is poorly understood. We previously showed that, following immunisation with radiation attenuated sporozoites (RAS), a model epitope embedded in a sporozoite surface protein elicited robust CD8⁺ T cell responses, whilst the same epitope in a liver stage antigen induced inferior responses. Since RAS arrest early in their development in host hepatocytes, we hypothesised that extending parasite maturation in the liver could considerably improve the epitope-specific CD8⁺ T cell response. Here, we employed a late liver stage arrested parasite model, azithromycin prophylaxis alongside live sporozoites, to increase expression of the model epitope until full liver stage maturation. Strikingly, this alternative immunisation strategy, which has been shown to elicit superior protection, failed to improve the resulting epitope-specific CD8⁺ T cell responses. Our findings support the notion that liver stage antigens are poorly immunogenic and provide additional caution about prioritising antigens for vaccine development based solely on immunogenicity.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2021 The Authors. *Parasite Immunology* published by John Wiley & Sons Ltd.

1 | INTRODUCTION

The malaria pre-erythrocytic stages are comprised of the extracellular sporozoites, which are inoculated by infected mosquitoes to the mammalian host, followed by the intracellular exo-erythrocytic forms (EEF; also known as liver stages), resulting from the development and maturation of sporozoites within a parasitophorous vacuole (PV) in hepatocytes.¹ Whilst there is an abundance of investigations delineating *Plasmodium* sporozoite antigens, the immune responses they induce, and their potential for use in malaria pre-erythrocytic vaccines,^{2–9} little is known about antigens solely expressed in EEFs.

Vaccination-induced protection against pre-erythrocytic stages was first shown to be feasible in animal models and humans using whole sporozoite vaccine approaches, particularly with radiation attenuation sporozoites (RAS),^{10–12} which are considered the benchmark for anti-malarial vaccines. Sterile protection induced by RAS has been shown to be mediated primarily by CD8⁺ T cells.^{13,14} Efficient recall of CD8⁺ T cell responses following presentation of parasite antigens on hepatocytes is crucial due to the short duration that the parasites are in the liver (~48–52 h for *P. berghei*¹⁵). Despite the high level of protection achieved, *P. berghei* RAS do not develop into large, mature hepatic schizonts but are arrested prior to onset of replication and growth approximately 24 h post-immunisation.^{16,17} This early hepatic arrest raises questions as to the magnitude of contributions of EEF-specific over sporozoite antigens in immunity.

Enhanced protection has been reported following the administration of anti-malarial chemoprophylaxis and live sporozoites in both animal models and in humans.^{18–21} Similar results have been reported after immunisations with late arresting genetically arrested sporozoites in preclinical studies in mice.^{22,23} Given that this alternative whole sporozoite vaccine approach ensures full EEF development, the results suggest that the longer the parasites are allowed to develop and mature before arrest, the greater the protection induced by the immunisation strategy. This outcome has been initially interpreted as having more antigens expressed and an increase in antigen biomass during extended parasite development, eliciting a broader range of EEF-specific immune responses needed for protection.^{22,23} However, immunogenic proteins expressed in the late EEF, which may increase CD8⁺ T cell responses, are currently not well defined.

The circumsporozoite protein (CSP) is the major surface coat antigen of sporozoites and upregulated in sporozoites 4 (UIS4) is a protein mainly associated with the parasitophorous vacuole membrane (PVM) surrounding the EEF.^{24,25} Upon *P. berghei* sporozoite infections of H-2K^b restricted C57BL/6 mice, no immunodominant epitopes in either CSP or UIS4 were identified.²⁶ Thus, in the absence of known EEF epitopes allowing for the quantification of specific T cell responses following sporozoite immunisation, we and others have used a surrogate marker, that is the upregulation of CD11a, in combination with the downregulation of CD8 α , as a durable and 'accurate' phenotyping method for infection or vaccine induced antigen-experienced T cells.^{27,28} To understand the

immunogenicity of EEF-specific antigens, as proxies for detecting CD8⁺ T cell epitopes in sporozoite and EEF antigens, we previously generated *P. berghei* transgenic parasites that express the SIINFEKL epitope from ovalbumin as part of either CSP or UIS4, CSP^{SIINFEKL} and UIS4^{SIINFEKL}, respectively.²⁹ Following RAS immunisation, a striking difference between the larger SIINFEKL-specific CD8⁺ T cell response elicited by CSP^{SIINFEKL} and the smaller response induced by UIS4^{SIINFEKL} was found. This divergence could be due to the abrupt cessation of or limited UIS4 expression following early arrest of RAS.

In this report, we tested the hypothesis that prolonged PVM protein expression increases CD8⁺ T cell responses against EEF vacuolar membrane proteins. Using CSP^{SIINFEKL} and UIS4^{SIINFEKL}, we compared the resulting CD8⁺ T cell responses, both in the spleen and in the liver, following RAS immunisation or infection with live parasites under azithromycin (AZ/Spz) prophylaxis, which is an apicoplast-targeting, delayed death-inducing anti-malarial drug allowing for the complete maturation of EEFs in the liver.³⁰

2 | MATERIALS AND METHODS

2.1 | Ethics and animal experimentation

Animal experiments performed in the United Kingdom were conducted under licence from the United Kingdom Home Office under the Animals (Scientific Procedures) Act 1986. Animal experiments in Germany were conducted in accordance with the German Tierschutzgesetz in der Fassung von 18. Mai 2006 (BGB1. I S. 1207), which implements the Directive 86/609/EEC from the European Union and the European Convention for the protection of vertebrate animals used for experimental and other scientific purposes. All protocols were approved by the Animal Welfare and Ethics Review Board of the London School of Hygiene and Tropical Medicine and the ethics committee of the Max Planck Institute for Infection Biology. NMRI, CD-1 and C57BL/6 laboratory mouse strains were bred in house at LSHTM or purchased from Charles River Laboratories (Margate). NMRI and CD-1 were used for cycling of parasites between vertebrate and mosquito hosts. Female C57BL/6 mice were used for immunology experiments at age 6–8 weeks.

2.2 | *P. berghei* ANKA immunisation

P. berghei WT, CSP^{SIINFEKL} and UIS4^{SIINFEKL} (strain ANKA; clone c15cy1) parasites²⁹ were maintained by continuous cycling between murine hosts (NMRI or CD-1) and *Anopheles stephensi* mosquitoes, as previously described.²⁹ Mice were immunised with 10,000 freshly isolated sporozoites intravenously in the lateral tail vein. Sporozoites were either γ -irradiated at 1.2×10^4 cGy or administered under prophylactic AZ cover. Azithromycin (Pfizer) was administered at a dose of 240 mg/kg intraperitoneally on the same day as parasite inoculation and one day after.³⁰

2.3 | Infection of Huh7 hepatoma cells with *P. berghei* sporozoites

In vitro infections were performed in Huh7 cells that were grown in 8-well Lab-Tek slides (30,000 cells/well). Freshly dissected sporozoites (10,000) were added to the cells in complete DMEM medium (10% FCS, 1% Pen/Strep) in duplicates. Parasites were added in medium containing AZ (1.5 μ M; Pfizer) or were subjected to γ -irradiation (1.2 \times 10⁴ cGy) prior to cell infection. Untreated sporozoites served as control. Huh7 cells were incubated for 1 h at room temperature to allow sporozoite sedimentation and at 37°C for additional 2 h to permit parasite entry. Infected cells were incubated in complete medium at 37°C for 48 h. Incubation was terminated by fixation in 4% paraformaldehyde. The infected cells were stained with a monoclonal mouse anti-*Pb*HSP70 antibody³¹ followed by a goat Alexa Fluor 488-labelled anti-mouse secondary antibody to visualise parasites, and with a rabbit anti-*Pb*UIS4 serum³² followed by goat Alexa Fluor 546-labelled anti-rabbit secondary antibody to delineate the PV. Hoechst 33342 was used to locate the nuclei. >20 individual images of EEFs per group were acquired using a Zeiss Axio Vision microscope at 63x magnification and 100 ms exposure at an excitation wavelength of 590 nm and an emission wavelength of 617 nm. The UIS4 fluorescence signal intensities, as proxies for protein amounts, were measured with Fiji ImageJ (NIH, Bethesda). UIS4 stained liver stages were surrounded with the free hand tool; "RawIntDen" value for each EEF (representing the sum of intensity units in the selected areas) was determined.

2.4 | Quantification of SIINFEKL-specific CD8⁺ T cell responses

Spleens and livers perfused with 5 ml PBS were harvested from immunised and naive mice and filtered by passing the organs through 70 μ m cell strainers (Corning). Liver-infiltrating lymphocytes were isolated following published protocols using a Percoll gradient.³³ Following red blood cell lysis and resuspension in complete media, cells were diluted in Trypan Blue (ThermoFisher Scientific) and counted by microscopy using a Neubauer 'Improved' haemocytometer (Biochrom) or cells were counted using a MACSQuant flow cytometer (Miltenyi Biotec), using propidium iodide (PI) (Sigma Aldrich) and CD45.2-Alexa647 (Biolegend) to distinguish between hepatocytes and lymphocytes. A total number of 2–3 \times 10⁶ splenocytes or 0.5–1 \times 10⁶ liver-infiltrating cells were plated in flat bottom 96-well plates and incubated with peptides at final concentration 10 μ g/ml in the presence of Brefeldin A (eBioScience). SIINFEKL peptide was synthesised and purchased from Peptides and Elephants (Hennigsdorf). Cells were incubated at 37°C, 5% CO₂ for 5–6 h. Cells were initially stained for cell surface markers, then for intracellular IFN- γ . Between stainings, cells were fixed with 4% paraformaldehyde and permeabilised using PermWash (BD). Data were acquired by flow cytometry using an LSRII or LSRFortessa (BD). Antibodies used for stainings were obtained from BD: CD3 (500A2) or eBioScience: CD8a (53–6.7), CD11a (M17/4), IFN- γ (XMG1.2).

2.5 | Statistics

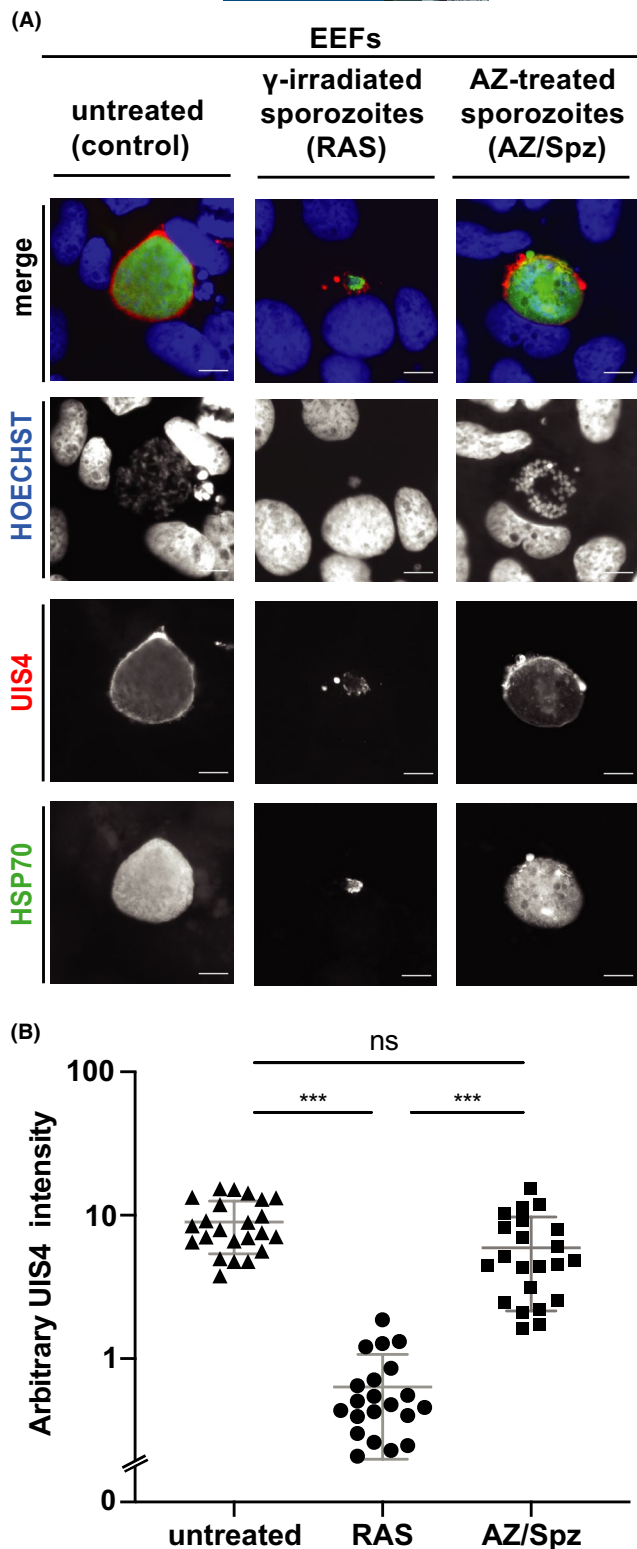
Data were analysed using FlowJo version 10.0.8 (Tree Star Inc.), Microsoft Excel and GraphPad Prism v9 (GraphPad Software Inc.). Statistics were calculated using one-way ANOVA with Tukey's multiple comparison test. Normality was calculated using the Shapiro-Wilk test.

3 | RESULTS AND DISCUSSION

We first compared the EEF development in vitro of RAS versus sporozoites with AZ (Figure 1). Irrespective of the method used, sporozoites retained their invasive capacities. Forty eight h after infection, as expected, morphological analysis revealed normal EEF differentiation by both untreated sporozoites and sporozoites cultured with AZ; large, mature hepatic schizonts, which underwent multiple nuclear divisions and surrounded by remodelled PV, as shown by UIS4 staining, were observed.³⁰ In contrast, RAS gave rise to arrested EEFs, which had reduced growth and showed absence of nuclear divisions.¹⁷ Despite this developmental arrest, these small, round intracellular parasites expressed HSP70 in their cytoplasm and are surrounded by a UIS4 containing remodelled PV, comparable to untreated parasites at earlier stages of intracellular development²⁹ (Figure 1A). The striking differences in parasite maturation in the liver rather suggest a higher amount of EEF-specific antigens upon AZ treatment. We quantified UIS4 protein levels by measuring the UIS4 fluorescence intensity over the area of individual EEFs. We show that UIS4 protein levels were comparable in AZ treated and untreated control EEFs, but significantly lower in RAS (Figure 1B). For the subsequent experiments, we compared the CD8⁺ T cell responses induced following RAS immunisation or sporozoites with AZ, utilising the *Pb*CSP^{SIINFEKL} and *Pb*UIS4^{SIINFEKL} parasites we previously generated.²⁹

We then measured the in vivo magnitude of antigen-experienced cells after parasite immunisation. Immunisation with both RAS or sporozoites under AZ cover, produced quantifiable CD11a^{hi} CD8⁺ (CD8 α^{lo}) T cells, around 8% in the spleen (Figure 2A,C,E) and 30% in the liver (Figure 2B,D,F), 2 weeks after immunisation as compared to 5% and 20%, respectively, in naive mice. These findings are consistent with previous work showing that both RAS and AZ attenuation induce comparable high levels of antigen-experienced CD8⁺ T cells in peripheral blood following immunisation.²¹

Next, we compared epitope-specific CD8⁺ T cell responses by ex vivo stimulation with SIINFEKL peptide (Figure 3). Consistent with our previous work,²⁹ following RAS immunisation, significantly higher proportions and numbers of SIINFEKL-specific IFN- γ -producing CD8⁺ T cells were induced with *Pb*CSP^{SIINFEKL} as compared to *Pb*UIS4^{SIINFEKL} (Figure 3A-D). Notably, extension of antigen availability and/or increased antigen biomass, due to prolonged UIS4 expression permitted by AZ administration, did not improve the proportions and numbers of IFN- γ producing CD8⁺ T cells, as compared to RAS immunisation. Together, these results clearly



demonstrate that extending EEF development, resulting in elevated vacuolar membrane antigen expression, does not amplify IFN- γ producing CD8⁺ T cell responses.

Whole-parasite immunisation strategies that allow the parasite to complete EEF development in the liver ensure immunisation against many antigens expressed in the pre-erythrocytic stages. These span from those expressed by the sporozoite to those expressed very late in

FIGURE 1 *Plasmodium berghei* liver stage development 48 h after co-administration of live sporozoites and azithromycin or administration of irradiation treated sporozoites. (A) Composite (top) and single channel fluorescence micrographs of WT *Plasmodium berghei* liver stages in cultured hepatoma cells. Shown are representative images of liver stages 48 h after infection with untreated sporozoites (control), irradiated sporozoites (RAS), and sporozoites with azithromycin cover (AZ/Spz) visualised by fluorescent staining of the cytoplasm (green; anti-PbHSP70 antibody), the parasitophorous vacuolar membrane (red; anti-PbUIS4 anti-serum), and nuclei (blue; Hoechst 33342). Scale bars: 10 μ m. (B) Dot plot illustrating the arbitrary UIS4 fluorescence signal intensity of single liver stages as a proxy for UIS4 protein amounts ($n = >20$ each) at 48 h after infection with untreated sporozoites (control), RAS, or AZ/Spz. The UIS4 signal was measured as the sum of the fluorescence signal intensity per pixel over the complete liver stage area in ImageJ. Bars and lines represent mean values \pm SD. ***, $p < .001$; ns, non-significant (One-way ANOVA with Tukey's multiple comparison test)

the EEF prior to merozoite release into the blood, as well as those antigens that are expressed throughout the pre-erythrocytic stages. Given that CD8⁺ T cells are crucial for protection against pre-erythrocytic stages, these strategies were originally thought to augment the pool of immunisation-induced CD8⁺ T cells that are specifically targeted against EEF antigens.¹⁸ However, we have demonstrated poor CD8⁺ T cell responses to an epitope contained within UIS4, a PVM protein expressed constitutively in the liver following sporozoite invasion of a hepatocyte.²⁹ We show that AZ prophylaxis would have allowed UIS4 to increase in size for the full 48–52 h of EEF development, in contrast to ~24 h when RAS were used. Despite these striking differences in parasite development, adaptive immune responses to sporozoite immunisation remained unaltered as evidenced by the comparable numbers of antigen-experienced CD8⁺ T cells, based on the quantification of CD11a proxy marker co-expression. These results are consistent with our previous findings that responses to UIS4 could not be enhanced by increasing the dose of RAS used for immunisation either.²⁹

We hypothesised that extending parasite maturation in the liver might improve the epitope-specific CD8⁺ T cell response. It is noteworthy that in order to obtain direct evidence for prolonged antigen exposure in sporozoites attenuated by AZ cover *versus* RAS immunisations, elution of MHC-bound peptides from infected hepatocytes over time could be performed. Thus far, elution of MHC-bound epitopes from dendritic cells that had been co-cultured with asexual blood stages has been achieved.³⁴ Establishing this approach for pre-erythrocytic antigens and in a time-course experiment will be considerably more challenging. Our data showing that AZ prophylaxis failed to improve the resulting epitope-specific CD8⁺ T cell responses, lending further support to the notion that liver stage antigens are poorly immunogenic.

AZ has been shown to specifically impede the biogenesis and inheritance of the apicoplast in malaria liver stages; EEFs continue to develop, but blood stage infection is not established.³⁰ In vitro work has indicated that AZ treatment of *P. berghei*-infected hepatoma cells allows for the detachment of merozoite-containing infected liver cells, and these merozoites fail to initiate blood stage

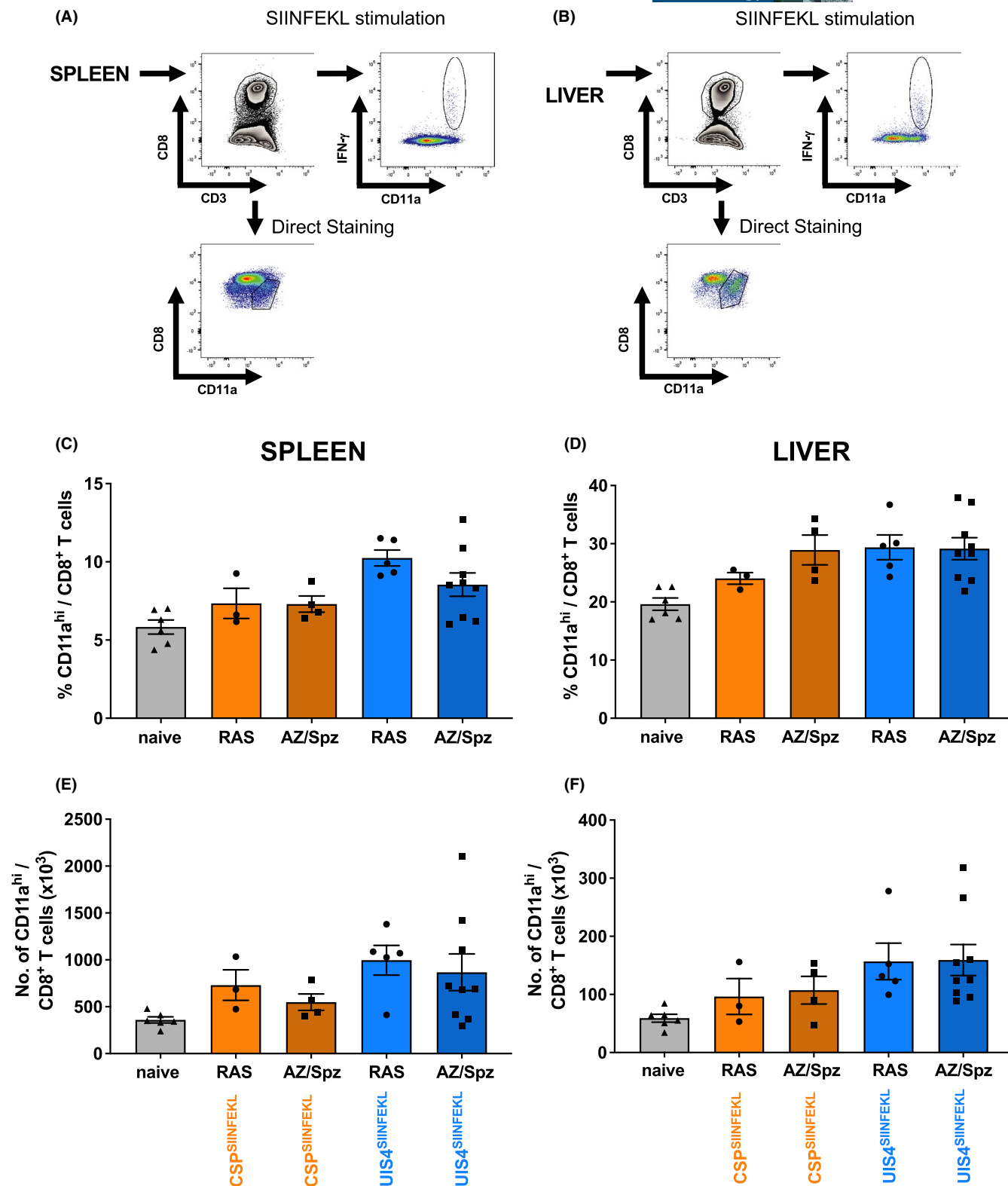


FIGURE 2 Induction of antigen-experienced CD8⁺ T cells to sporozoite and EEF vacuolar antigens following different methods of sporozoite attenuation. (A,B) The flow cytometry gating strategy used to assess the proportion of antigen-experienced CD8⁺ T cells (CD11a^{hi} CD8 α ^{lo}) and IFN- γ producing antigen-specific CD8⁺ T cells (IFN- γ ⁺ CD11a⁺) in the (A) spleen and (B) liver. (C-F) Mice were immunised with CSP^{SIINFEKL} ($n = 3-4$) or UIS4^{SIINFEKL} ($n = 5-9$) RAS or AZ/Spz. Spleens and livers from immunised and naïve mice were harvested 14 days later. Graphs show the (C,D) percentage and (E,F) absolute cell counts of CD11a^{hi} CD8 α ^{lo} cells from the CD8⁺ T cell compartment in the (C,E) spleen and (D,F) liver. Bar charts show mean values (\pm SEM). One-way ANOVA with Tukey's multiple comparison test was employed with no statistical significance between groups determined. Values shown are from one representative experiment from at least two independently conducted experiments

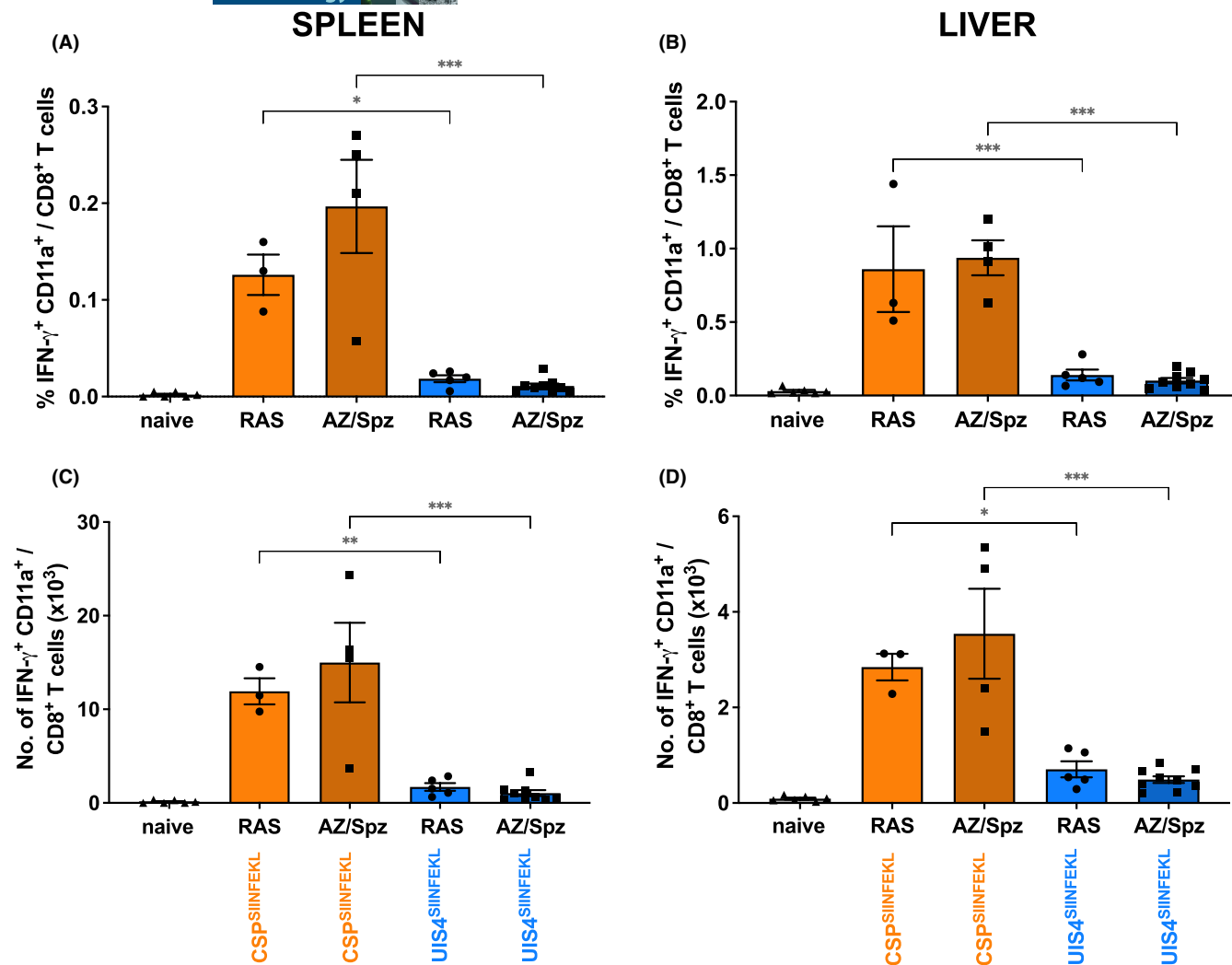


FIGURE 3 Generation of antigen-specific CD8⁺ T cells to sporozoite and EEF vacuolar antigens following different methods of sporozoite attenuation. Mice were immunised with CSP^{SIINFEKL} ($n = 3-4$) or UIS4^{SIINFEKL} ($n = 5-9$) RAS or AZ/Spz. Spleens and livers from immunised and naïve mice were harvested 14 days later. Lymphocytes were restimulated with SIINFEKL and stained for flow cytometry. The graphs show the (A,B) percentage and (C,D) absolute cell counts of CD11a^{hi} CD8 α ^{lo} cells co-expressing IFN- γ in the (A,C) spleen and (B,D) liver. Bar charts show mean values (\pm SEM). * $p < .05$; ** $p < 0.01$; *** $p < 0.001$; one-way ANOVA with Tukey's multiple comparison test). Values shown are from one representative experiment of at least two independently conducted experiments

patency.³⁰ The immunogenicity of these merozoites is of interest, particularly because mice immunised with sporozoites under AZ cover are susceptible to blood-stage challenge, demonstrating that protective immunity offered by this form of parasite attenuation is primarily against the pre-erythrocytic stages and that CD8⁺ T cells are the prime effector mechanisms.²¹

In contrast, immunisation with sporozoites under chloroquine (CQ) cover also leads to full EEF development and successful initial blood infection. Accordingly, recent studies revealed the generation of cross-stage protection involving both pre-erythrocytic and blood stages.^{35,36} Understanding the extent to which blood stage antigens are exposed to the immune system following immunisation with whole sporozoites is important to the identification of vaccination strategies that can combine T cell responses against the pre-erythrocytic stages and antibodies against sporozoites and blood stages.

This study provides a confirmation that EEF antigens are poorly immunogenic. Yet, CD8⁺ T cells must recognise peptides directly

processed and presented by parasitised hepatocytes to employ their protective functions. Taken together with our recent findings that EEF antigens are nonetheless excellent targets of vaccine-induced CD8⁺ T cells,²⁹ our results challenge the use of immunogenicity in prioritising antigens for the design and evaluation of next-generation pre-erythrocytic vaccines. Standard immunological assays, endeavoured at discovering highly immunogenic antigens, may fail to identify those candidates with the ability to evoke superior levels of protective immunity. An in-depth characterisation of the complex biology of pre-erythrocytic stages, the immune responses they generate or not, coupled with a strategic identification of vaccine targets, should drive progress towards a highly efficacious malaria vaccine.

ACKNOWLEDGEMENTS

We would like to thank Jason Mooney for his critical reading of the manuscript. Kai Matuschewski was supported by the Max Planck

Society and grants from the European Commission (EviMalaR Network of Excellence #34) and the Chica and Heinz Schaller Foundation. Olivier Silvie was funded in part by the Laboratoire d'Excellence ParaFrap (ANR-11-LABX-0024). Julius Hafalla was funded by grants from The Royal Society (University Research Fellowship UF0762736/UF120026 and Project Grant RG130034) and the National Centre for the Replacement, Refinement & Reduction of Animals in Research (Project Grant NC/L000601/1). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1111/pim.12877>.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Matthew P. Gibbins  <https://orcid.org/0000-0002-7166-044X>

Katja Müller  <https://orcid.org/0000-0001-5100-0981>

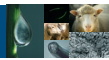
Kai Matuschewski  <https://orcid.org/0000-0001-6147-8591>

Olivier Silvie  <https://orcid.org/0000-0002-0525-6940>

Julius Clemence R. Hafalla  <https://orcid.org/0000-0002-5452-9263>

REFERENCES

- Hafalla JC, Silvie O, Matuschewski K. Cell biology and immunology of malaria. *Immunol Rev*. 2011;240(1):297-316.
- Zavala F, Cochrane AH, Nardin EH, Nussenzweig RS, Nussenzweig V. Circumsporozoite proteins of malaria parasites contain a single immunodominant region with two or more identical epitopes. *J Exp Med*. 1983;157(6):1947-1957.
- Herrington DA, Clyde DF, Losonsky G, et al. Safety and immunogenicity in man of a synthetic peptide malaria vaccine against *Plasmodium falciparum* sporozoites. *Nature*. 1987;328(6127):257-259.
- Romero P, Maryanski JL, Corradin G, Nussenzweig RS, Nussenzweig V, Zavala F. Cloned cytotoxic T cells recognize an epitope in the circumsporozoite protein and protect against malaria. *Nature*. 1989;341(6240):323-326.
- RTS S Clinical Trials Partnership. Efficacy and safety of the RTS, S/AS01 malaria vaccine during 18 months after vaccination: a phase 3 randomized, controlled trial in children and young infants at 11 African sites. *PLoS Medicine*. 2014;11(7):e1001685.
- Dunachie SJ, Walther M, Epstein JE, et al. A DNA prime-modified vaccinia virus ankara boost vaccine encoding thrombospondin-related adhesion protein but not circumsporozoite protein partially protects healthy malaria-naïve adults against *Plasmodium falciparum* sporozoite challenge. *Infect Immun*. 2006;74(10):5933-5942.
- Ogwang C, Kimani D, Edwards NJ, et al. Prime-boost vaccination with chimpanzee adenovirus and modified vaccinia Ankara encoding TRAP provides partial protection against *Plasmodium falciparum* infection in Kenyan adults. *Sci Transl Med*. 2015;7(286):286re285.
- Bergmann-Leitner ES, Legler PM, Savranskaya T, Ockenhouse CF, Angov E. Cellular and humoral immune effector mechanisms required for sterile protection against sporozoite challenge induced with the novel malaria vaccine candidate CeLTOS. *Vaccine*. 2011;29(35):5940-5949.
- Espinosa DA, Vega-Rodriguez J, Flores-Garcia Y, et al. The *Plasmodium falciparum* Cell-traversal protein for ookinetes and sporozoites as a candidate for preerythrocytic and transmission-blocking vaccines. *Infect Immun*. 2017;85(2):e00498-e00516.
- Nussenzweig RS, Vanderberg J, Most H, Orton C. Protective immunity produced by the injection of x-irradiated sporozoites of *Plasmodium berghei*. *Nature*. 1967;216(5111):160-162.
- Gwadz RW, Cochrane AH, Nussenzweig V, Nussenzweig RS. Preliminary studies on vaccination of rhesus monkeys with irradiated sporozoites of *Plasmodium knowlesi* and characterization of surface antigens of these parasites. *Bull World Health Organ*. 1979;57(Suppl. 1):165-173.
- Clyde DF, Most H, McCarthy VC, Vanderberg JP. Immunization of man against sporozoite-induced falciparum malaria. *Am J Med Sci*. 1973;266(3):169-177.
- Schofield L, Villaquiran J, Ferreira A, Schellekens H, Nussenzweig R, Nussenzweig V. Gamma interferon, CD8+ T cells and antibodies required for immunity to malaria sporozoites. *Nature*. 1987;330(6149):664-666.
- Doolan DL, Hoffman SL. The complexity of protective immunity against liver-stage malaria. *J Immunol*. 2000;165(3):1453-1462.
- Landau I, Boulard Y. Life cycles and Morphology. In: Killick-Kendrick R, Peters W, (Eds.). *Rodent Malaria*. Academic Press; 1978:53-84.
- Suhrbier A, Winger LA, Castellano E, Sindén RE. Survival and antigenic profile of irradiated malarial sporozoites in infected liver cells. *Infect Immun*. 1990;58(9):2834-2839.
- Silvie O, Semblat JP, Franetich JF, Hannoun L, Eling W, Mazier D. Effects of irradiation on *Plasmodium falciparum* sporozoite hepatic development: implications for the design of pre-erythrocytic malaria vaccines. *Parasite Immunol*. 2002;24(4):221-223.
- Roestenberg M, McCall M, Hopman J, et al. Protection against a malaria challenge by sporozoite inoculation. *N Engl J Med*. 2009;361(5):468-477.
- Bijker EM, Bastiaens GJ, Teirlinck AC, et al. Protection against malaria after immunization by chloroquine prophylaxis and sporozoites is mediated by preerythrocytic immunity. *Proc Natl Acad Sci U S A*. 2013;110(19):7862-7867.
- Belnoue E, Costa FT, Frankenberg T, et al. Protective T cell immunity against malaria liver stage after vaccination with live sporozoites under chloroquine treatment. *J Immunol*. 2004;172(4):2487-2495.
- Friesen J, Matuschewski K. Comparative efficacy of pre-erythrocytic whole organism vaccine strategies against the malaria parasite. *Vaccine*. 2011;29(40):7002-7008.
- Haussig JM, Matuschewski K, Kooij TW. Inactivation of a plasmodium apicoplast protein attenuates formation of liver merozoites. *Mol Microbiol*. 2011;81(6):1511-1525.
- Butler NS, Schmidt NW, Vaughan AM, Aly AS, Kappe SH, Harty JT. Superior antimalarial immunity after vaccination with late liver stage-arresting genetically attenuated parasites. *Cell Host Microbe*. 2011;9(6):451-462.
- Mueller AK, Camargo N, Kaiser K, et al. *Plasmodium* liver stage developmental arrest by depletion of a protein at the parasite-host interface. *Proc Natl Acad Sci U S A*. 2005;102(8):3022-3027.
- Silvie O, Briquet S, Muller K, Manzoni G, Matuschewski K. Post-transcriptional silencing of UIS4 in *Plasmodium berghei* sporozoites is important for host switch. *Mol Microbiol*. 2014;91(6):1200-1213.
- Hafalla JC, Bauza K, Friesen J, Gonzalez-Aseguinolaza G, Hill AV, Matuschewski K. Identification of targets of CD8(+) T cell responses to malaria liver stages by genome-wide epitope profiling. *PLoS Pathog*. 2013;9(5):e1003303.
- Rai D, Pham NL, Harty JT, Badovinac VP. Tracking the total CD8 T cell response to infection reveals substantial discordance in



- magnitude and kinetics between inbred and outbred hosts. *J Immunol.* 2009;183(12):7672-7681.
28. Schmidt NW, Butler NS, Badovinac VP, Harty JT. Extreme CD8 T cell requirements for anti-malarial liver-stage immunity following immunization with radiation attenuated sporozoites. *PLoS Pathog.* 2010;6(7):e1000998.
 29. Muller K, Gibbins MP, Roberts M, et al. Low immunogenicity of malaria pre-erythrocytic stages can be overcome by vaccination. *EMBO Mol Med.* 2021;13(4):e13390.
 30. Friesen J, Silvie O, Putrianti ED, Hafalla JC, Matuschewski K, Borrmann S. Natural immunization against malaria: causal prophylaxis with antibiotics. *Sci Transl Med.* 2010;2(40):40ra49.
 31. Tsuji M, Mattei D, Nussenzweig RS, Eichinger D, Zavala F. Demonstration of heat-shock protein 70 in the sporozoite stage of malaria parasites. *Parasitol Res.* 1994;80(1):16-21.
 32. Montagna GN, Beigier-Bompadre M, Becker M, Kroczeck RA, Kaufmann SH, Matuschewski K. Antigen export during liver infection of the malaria parasite augments protective immunity. *MBio.* 2014;5(4):e01321-e1314.
 33. Goossens PL, Jouin H, Marchal G, Milon G. Isolation and flow cytometric analysis of the free lymphomyeloid cells present in murine liver. *J Immunol Methods.* 1990;132(1):137-144.
 34. Valencia-Hernandez AM, Ng WY, Ghazanfari N, et al. A natural peptide antigen within the *Plasmodium* ribosomal protein RPL6 confers liver T_{RM} cell-mediated immunity against malaria in mice. *Cell Host Microbe.* 2020;27(6):950-962.
 35. Doll KL, Butler NS, Harty JT. CD8 T cell independent immunity after single dose infection-treatment-vaccination (ITV) against *Plasmodium yoelii*. *Vaccine.* 2014;32(4):483-491.
 36. Nahrendorf W, Spence PJ, Tumwine I, et al. Blood-stage immunity to *Plasmodium chabaudi* malaria following chemoprophylaxis and sporozoite immunization. *Elife.* 2015;4.

How to cite this article: Gibbins MP, Müller K, Matuschewski K, Silvie O, Hafalla JCR. Inferior T cell immunogenicity of a *Plasmodium berghei* model liver stage antigen expressed throughout pre-erythrocytic maturation. *Parasite Immunol.* 2021;00e1-8. <https://doi.org/10.1111/pim.12877>